Lightweight portable hyperbaric chambers

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Abstract

To protect divers and submariners suffering from decompression illness (DCI) in remote areas, far from a medical centre, it is critical to begin hyperbaric therapy as soon as possible. Since many fatalities involved in diving accidents result from delays in treatment, portable lightweight hyperbaric chambers have been developed. With modern technology, such as new materials, and with different operational conditions and dimensions, recompression chambers can be designed to operate in any location, such as on a ship, in a helicopter, or on an airplane, as a hyperbaric stretcher to evacuate the patient under pressure. There are a number of such chambers. The objective of the present report is to review and describe the principal characteristics and capabilities of all existing portable hyperbaric chambers, including the ones used for medical and private operations. The literature review has identified approximately 20 collapsible chambers which are either inflatable or modular. Some of them are fully operational while others are still in prototype or patent state. The outcome of this review is to identify methods and new developments in engineering with the aim of designing and building a new multi-person hyperbaric emergency treatment facility for submarine escape and rescue.

Résumé

Pour protéger les plongeurs et les sous-mariniers souffrant de la maladie de décompression en régions éloignées, loin d'un centre médical, il est critique d'amorcer un traitement hyperbare le plus tôt possible. Comme de nombreux décès ou lésions permanentes associés à des accidents de plongée sont dus à des retards dans la mise en route d'un traitement, des caissons hyperbares légers portatifs ont été mis au point. Grâce à la technologie moderne, notamment à de nouveaux matériaux, et en tenant compte de différentes dimensions et conditions opérationnelles, il est possible de concevoir des caissons de recompression qui peuvent fonctionner partout, p. ex. sur un navire, un hélicoptère, un aéronef, ou servir de brancard hyperbare pour évacuer le patient sous pression. Il existe un certain nombre de caissons de ce type. L'objectif du présent rapport est de passer en revue et de décrire les principales caractéristiques et fonctions de tous les caissons hyperbares portatifs existants, y compris ceux utilisés pour des opérations médicales et privées. Un dépouillement de la littérature nous a permis de recenser environ 20 caissons gonflables ou modulaires. Certains d'entre eux sont tout à fait opérationnels alors que d'autres en sont encore au stade du prototype ou du brevet. Le but de cette revue de la littérature est de déterminer les méthodes et les innovations en génie qui permettraient de mettre au point et de construire de nouvelles installations de traitement hyperbare d'urgence pour plusieurs personnes qui pourraient servir lors d'évacuation et sauvetage de sous-marins.

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Executive summary

Whenever divers or escapees from a distressed submarine (DISSUB) show symptoms of decompression illness[1] (DCI), it is essential for them to receive prompt treatment to prevent potential permanent injury or even death. They will need to receive rapid hyperbaric treatment on site and/or be evacuated under pressure to a stationary recompression chamber sited ashore close to naval harbours or hospitals. A recompression chamber is therefore required in all circumstances.

Until recently, recompression chambers have been large, heavy and rigid structures. Transporting them quickly to areas where they would be needed, such as in a submarine escape situation, would be very arduous and would take a considerable amount of time. Due to their flexibility, recently developed portable collapsible hyperbaric chambers possess advantages over the available steel-welded recompression chambers in **PORTABILITY**, **SIZE**, **WEIGHT** and **COST**. The material used for their construction is important. It has to provide the required combination of: lightness in weight, flexibility and toughness in use, non-toxicity to humans, and low flammability characteristics.

A variety of portable lightweight hyperbaric chambers have been designed and manufactured. Most of them allow treatments for one to two patients only. They have principally cylindrical or spherical walls so as to eliminate or minimize any stress concentration. Approximately 20 collapsible recompression chambers have been identified. Being either inflatable or modular, they have been divided into four groups: operational manufactured chambers, the ones strictly used by the US government agencies, the patented ones, and finally the clinical and private medical chambers. Owing to the inadequacy of the current hyperbaric capability of the CF in the case of a submarine escape and the lack of associated facilities, methods identified in the present review and the latest technology used, such as new materials will allow establishing design parameters for a treatment facility to provide a rapidly-deployable, collapsible, multi-person chamber for remote DCI and casualty treatment.

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[1] Decompression Illness (DCI) includes both Decompression Sickness (DCS) and Arterial Gas Embolism (AGE).

Sommaire

Lorsque les plongeurs ou les personnes qui évacuent un sous-marin en détresse (DISSUB) présentent des symptômes de maladie de décompression[2], il est essentiel de leur administrer rapidement un traitement afin de prévenir des lésions permanentes possibles, voire le décès. Ils devront recevoir un traitement hyperbare rapide sur place et/ou être évacués sous pression vers un caisson de recompression stationnaire situé à terre près d'un port naval ou d'un hôpital. Un caisson de recompression est donc requis en toute circonstance.

Jusqu'à récemment, les caissons de recompression ont toujours eu des structures volumineuses, lourdes et rigides. Leur transport rapide vers des zones où ils sont requis, notamment en cas d'évacuation d'un sous-marin, serait très pénible et prendrait beaucoup de temps. En raison de leur flexibilité, les caissons hyperbares démontables portatifs récemment développés possèdent, par rapport aux caissons de recompression en acier soudé actuellement disponibles, des avantages sur le plan de la **PORTABILITÉ**, de la **TAILLE**, du **POIDS** et du **COÛT**. Le matériel utilisé pour leur construction est important. Il doit allier les caractéristiques requises suivantes : légèreté au niveau du poids, flexibilité et robustesse à l'usage, non-toxicité pour les humains et faible degré d'inflammabilité.

Divers caissons hyperbares légers et portatifs ont été conçus et fabriqués. La plupart d'entre eux permettent de dispenser des traitements à un ou deux patients seulement. Ils sont constitués principalement de parois cylindriques ou sphériques de façon à éliminer ou à réduire au minimum toute concentration de contraintes. Environ 20 caissons de recompression démontables ont été identifiés. Gonflables ou modulaires, ils ont été divisés en quatre groupes : caissons fabriqués qui sont opérationnels, ceux qui sont réservés strictement à l'usage des agences du gouvernement américain, les caissons brevetés et, enfin, les caissons médicaux à usage clinique et privé. Comme les FC sont incapables actuellement d'offrir un traitement hyperbare à toutes les personnes évacuant un sous-marin et qu'il n'y a pas d'installations adéquates pour ce faire, les méthodes identifiées dans la présente analyse et les dernières techniques utilisées, telles que les nouveaux matériaux, permettront d'établir les paramètres de conception pour une installation de traitement pouvant offrir un caisson multi-personne, démontable, rapidement déployable pour le traitement à distance de la maladie de décompression et de certaines blessures.

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[2] La maladie de décompression inclut à la fois le mal des caissons et l'embolie gazeuse artérielle.

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Acknowledgements

The author would like to thank Dave Eaton and Ronald Nishi for their valuable assistance in reviewing this report. Their comments and suggestions were helpful and encouraging.

1. Introduction

Divers and submariners may suffer from decompression illness (DCI) because of a rapid ascent to the surface thereby omitting the required decompression schedule. DCI is a physiological condition resulting from the formation of gas bubbles in the body following a rapid transition from high-pressure environment to a lower one. In fact, according to Henry's law[3], inert gas breathed at depth, at relatively high-pressure, dissolves and accumulates in body tissues. As the subject returns to the surface, the gas may form bubbles. While expanding (Boyle's law[4]), bubbles can disrupt blood circulation, block small vessels and cause pain and, in the worst case, death.

It is well known that a patient suffering from DCI needs to receive hyperbaric therapy. This is done through recompression to a specific depth followed by a slow decompression inside a hyperbaric chamber. The increased ambient pressure forces the body's fluids to absorb more oxygen, resulting in the increased partial pressure of oxygen in blood and tissues, inducing, as a result, off-gassing of inert gas.

Various recompression chambers have been developed and used. Few of them can be transported to remote areas. Commonly fabricated of welded steel, their structure is rigid and heavy, thereby transporting them when required would be very arduous and demanding. To improve the transport time and initiate treatment as fast as possible, it is preferable that hyperbaric chambers be fully collapsible and portable. In this respect, inflatable or modular ones are the most suitable since they possess advantages over the currently transportable chambers in portability, size, weight and cost.

A variety of portable lightweight recompression chambers have been produced or designed. Most of them typically have cylindrical or spherical walls so as to eliminate or minimize any stress concentration. This report, divided in four parts, presents a list of all existing collapsible, inflatable or modular, hyperbaric chambers and describes their principal characteristics and capabilities. The list also includes chamber designs that have been patented. The first part presents the operational manufactured chambers. The second part describes those designed and built for US government agencies, such as NASA. The third part describes chambers that have been patented but have not been produced for operational use. And finally, part four includes available chambers intended for clinical or private medical treatments. Tables A1-5, Annex A, show a summary of all hyperbaric chambers presented in this report.

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[3] Henry's law states that the solubility of a gas in a liquid is proportional to the partial pressure of the gas over the solution, provided that no chemical reaction occurs.

[4] Boyle's law states that at a constant temperature, the volume and the pressure of a gas are inversely proportional.

2. Collapsible or Modular Hyperbaric Chambers

2.1 Manufactured chambers

Chambers in this category are those that have been manufactured for civilian and military operations. They are aimed at treating DCI and/or evacuating the patient under pressure to a permanent recompression chamber located close to a hospital. The working pressure is equivalent to a depth of 18 m (60 ft), or 27 psi approximately, the pressure used in standard treatment tables. Because of their flexibility and portability, the principal characteristics of the material for these chambers are lightness and high strength.

2.1.1 SOS Hyperlite Hyperbaric Stretcher

This chamber (Figure 1) is inflatable using compressed air. It is employed for the treatment and/or transportation (evacuation) under pressure of one patient suffering from decompression sickness or gas embolism to a permanent recompression chamber. It comprises an elongated cylindrical casing (1) with end members (3 and 4). At least one of these two end members is removable to provide access to the interior of the chamber. The end members seal with minimal pressurization and are fixed by internal pressure without the need of a latch.

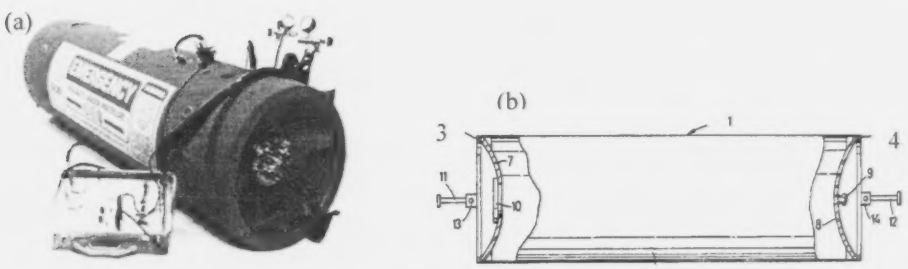

***Figure 1**. SOS Hyperlite hyperbaric stretcher (a from [1] and b from [2]).*

To be flexible, the casing (1) is made of silicone elastomer material (such as, General Electric SLE 5300, RTV 615 and RTV 630 or Dow Corning Ltd. Sylgard 182) reinforced with windings of reinforcing filaments, which may be, according to the patent [2], in the form of yarn of filaments. These filaments can be made of glass or high strength polymers such as Para-aramid (e.g., Kevlar®). They may be pre-impregnated with a silicone elastomer precursor. Abrasion-resistant inner and outer coats may be applied after the application of a gel coat to obtain a smooth surface to the casing.

The Hyperlite chamber comes equipped with a communication system, oxygen monitor, standard SCUBA tanks, which hold 77 ft^3 of gas, with securing racks and an oral-nasal mask designed to deliver pressurized breathing gases to the patient. The detailed specifications of this chamber are presented in Table B1, Annex B. Finally, as illustrated in Figure 2, two chambers can be connected using a tubular link. This would permit access to the patient from a second chamber without loss of pressure.

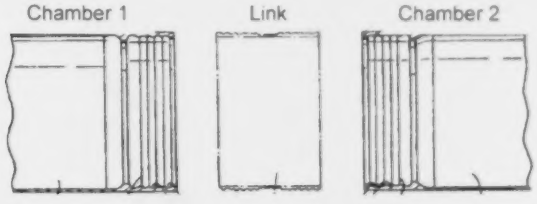

Figure 2. *Two Hyperlite hyperbaric chambers with their link [2].*

This hyperbaric chamber has been tested and evaluated by the US Air Force Research Laboratory (AFRL) [3], the US Navy Experimental Diving Unit (NEDU) [4 and 5] and the Royal Navy Defence Evaluation and Research Agency (DERA) (according to [5]). Furthermore, according to the manufacturer's website [1]:

- The Russian Navy has bought, after the tragic loss of Russian Submarine Kursk, five Hyperlite chambers for their new Submarine Rescue Project.
- The US Coast Guard has purchased six units for its dive team.
- All four services of the United States military are expected to purchase an unspecified number of Hyperlite chambers. Forty units are being procured to enable easier individual transfer under pressure (TUP) from the new US Deep Sea Rescue Vehicle (DSRV).
- Wyle Laboratories, under a NASA contract, bought one chamber to explore the feasibility of hyperbaric therapy in space, in particular, on the International Space Station.

Status: *Operational*
Inventors: *John F. Cardwell; Simon C. Martin; James H. C. Rowan; Riyadh N. Askander; John S. Selby.*
Manufacturer: *SOS Limited (London, UK)*

2.1.2 GSE Flexible Hyperbaric

Intended primarily for hyperbaric treatment [4 and 5], the GSE chamber (Figure 3) is flexible, collapsible and portable. According to the patent [9] the chamber comprises a flexible casing made of two layers of cloth, a ring and a removable hatch at one end (Figure 3b and 4b), and an endplate at the other end (Figure 4a). Made of aluminium alloy, both ring and endplate are permanently attached to the casing. The hatch is fixed to the ring with 1/8 turn interrupted thread "bayonet" fitting. The inner layer is made of a urethane-coated polyester cloth to prevent gas leakage. The outer layer is a net of woven polyester straps to provide longitudinal and transversal strength, and to maintain the shape. The detailed specifications of this chamber are presented in Table B1, Annex B.

This chamber provides the possibility of attaching a second chamber (Figure 3a), allowing a medical attendant to stay in the chamber with the patient under pressure.

The GSE chamber has been tested and evaluated by the US Navy Experimental Diving Unit (NEDU) [4-5] and Wyle Laboratories (under a NASA contract) [7]. It is interesting to note that when subjected to hydrostatic testing to failure, the chamber exploded at a pressure of 200 psig. This result gives a safety factor of 2.72, which is lower than the manufacturer provided data. Consequently, the working pressure was reduced to 30.5 psig (versus 70.5 psig as stated by the manufacturer).

Status: *Operational*
Inventor: *Giunio Santi Guido*
Manufacturer: *GSE Giunio Santi Engineering S.R.L. (IT)*

(a) (b)

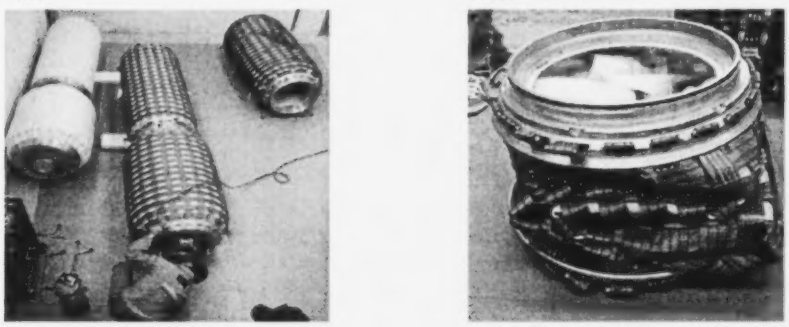

Figure 3. *The GSE flexible chamber [8].*

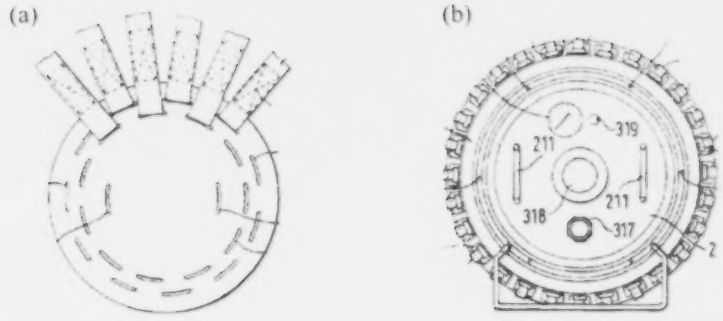

Figure 4. *Ends of the GSE flexible chamber [9]: (a): endplate; (b): hatch fixed to the ring.*

2.2 US government chambers

These chambers have been designed and produced for US government agencies. Most of them are at the prototype stage and still not operational. Nevertheless, they have been tested and evaluated.

2.2.1 ILC Dover Collapsible Hyperbaric Chamber

During the 1980's, ILC Dover designed and fabricated a hyperbaric chamber (Figure 5) for astronaut recovery. Due to weight and space limitations of the spacecraft, this chamber was designed to be lightweight, transportable and collapsible. Its configuration was cylindrical with hemispherical ends. The chamber's structure consisted of two layers, the inner one being a bladder to prevent gas leakage and the outer layer being a restraint for structural loads. The bladder was made of urethane-coated polyester, while the restraint was made of a series of polyester webbing stitched to a polyester fabric substrate. According to Graham [12], an ILC Dover Engineer, only one chamber was built; however, the construction technique has been applied to other projects. The detailed specifications of this chamber are presented in Table B1, Annex B.

Status: *Inactive (prototype only built)*

Inventor: *ILC Dover inc.*

Owner: *Constructed by ILC Dover inc. for NASA use only.*

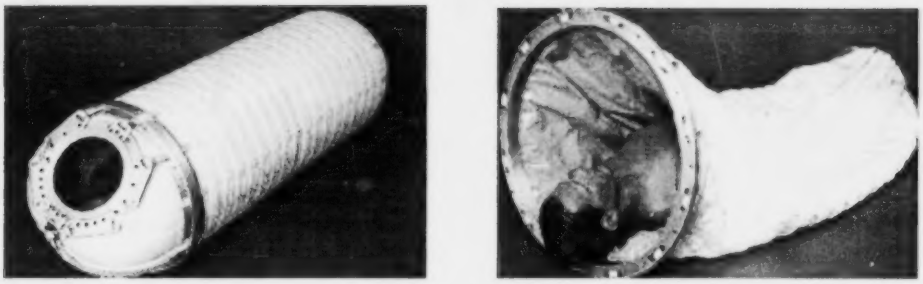

Figure 5. *ILC Dover Collapsible Hyperbaric Chamber [13].*

2.2.2 Lightweight, Collapsible Hyperbaric Chamber with Airlock System

According to the inventors [14-16] this system includes a main hyperbaric chamber and an airlock for a medical attendant (Figure 6), both capable of sustaining an interior pressure of 2 atm (29.4 psi). The hyperbaric chamber is collapsible and portable and can be stored in a small volume. It will have the capability to provide immediate treatment for decompression or altitude sickness for one patient. The structure of the chamber and the airlock will consist of an inner pressure-bladder (85 in Figure 7) to prevent gas leakage and circumferential and longitudinal flexible retaining straps (Figure 6a and 75 in Figure 7). Used for structural strength to withstand pressurization, these straps will be interwoven for extra strength and stability. Both the bladder and the straps will be attached to the hatch ring (50 in Figure 7).

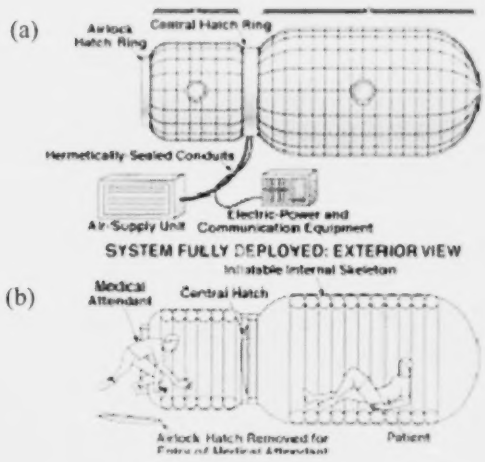

Figure 6. *Lightweight, collapsible hyperbaric chamber with airlock System [16].*

As shown in Figure 7a, each longitudinal strap (75) is secured to the hatch ring (50) with roller assemblies (90). Each roller assembly includes a roller (91) and a bracket (92). The bladder (85) is secured to the ring using a clamp (51). The hatch (55 in Figure 7b) is elliptical having a major axis and a minor axis. Its minor axis must be smaller than the major axis of the orifice (52) so as to facilitate its insertion.

Figure 7. *The Chamber's hatch and its ring; (a): The hatch ring with the straps roller attachments; (b): elliptical shape of the hatch [15].*

Finally to facilitate entry and egress of the patient, interconnected low-pressure inflatable toroids (or a single helical tube) are used as an internal skeleton to maintain the chamber and airlock in the expanded condition during the non-pressurized mode. In addition, these toroids could serve as a cushion for the patient during treatment (Figure 6b).

Status: *Patent (2001) + Prototype*

Inventor: *William C. Schneider, James P. Locke, and Horacio M. De La Fuente*

Owner: *The United States of America as represented by the Administrator of the National Aeronautics and Space Administration (NASA), Washington, DC, USA*

2.2.3 Modular, Expandable Hyperbaric Chamber System (MEHCS)

As an alternative to inflatable chambers, a Modular and Expandable Hyperbaric Chamber System (MEHCS) has been designed and constructed by (or for) the US Air Force [17]. This chamber, being composed of non-welded, traditional steel material, has several advantages:

1. It can be stored completely in sections, ready and easy to be rapidly transported and/or assembled.

2. It can be moved into a facility (such as hospital, ship, etc.) before assembly without having to alter the facility's structure (e.g., doors or walls) as is the case with traditional chambers.

3. Its configuration and size can be easily changed, for example, in the situation of increased casualties.

In addition to these advantages, this chamber has large and sliding doors for easy access and egress. Its walls are vertical, thus optimizing interior space. Designed for six persons, its working pressure is projected to be 3 ATA and its nominal dimensions are 8 by 11 feet. Because steel is used, its weight is approximately 14,000 lbs. According to the USAF Hyperbaric Newsletter, this chamber meets all the ASME-PVHO safety codes and its cost is assumed to be less than US$500,000. Furthermore in 1998, the newsletter's publication date, MEHCS was available, but was on hold in anticipation of its integration into the inventory before its deployment.

Status: *built*

Inventor and Owner: *US Air Force Laboratory*

2.3 Patented chambers

Chambers described here are those that have been patented but have not been produced for operational use. Various shapes, dimensions and innovative technologies have been suggested.

2.3.1 Modular and Polygonal Pressure Vessel

This hyperbaric chamber is modular and would be to transport and assemble. It has a ***polygonal*** cross-section (Figure 8) with a minimum of three connected sides forming the chamber. Each side is made of a single or multiple panels. Because the chamber is modular, its size can be changed simply by increasing or reducing the number of panels. The sides are flexibly interconnected using connectors (90) and tie rods (11 in Figure 8 and 9a and b). The connector assembly allows the connected sides at the juncture of the connector assembly to pivot or move relative to one another. They can rotate around an axis determined by a tie rod. In this case, the tie rod experiences only a shearing force, eliminating stress concentrations that would exist at the corners of a welded pressure vessel of polygonal cross section. Finally, a seal is used to form fluid-tight seals (114 in Figure 9) between adjacent panels.

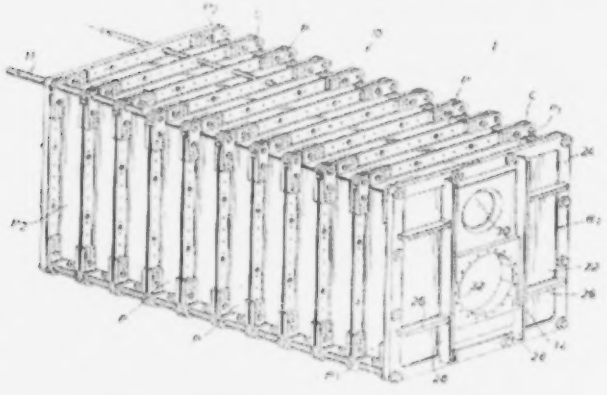

Figure 8. *Modular Pressure Vessel [18].*

According to the inventor [18 and 19], each panel can be made of metal, plastic, composites, fibreglass, concrete or any material with sufficient tensile strength.

Status: *Patent (2002)*
Inventor and Owner: *Audley L. Aaron*

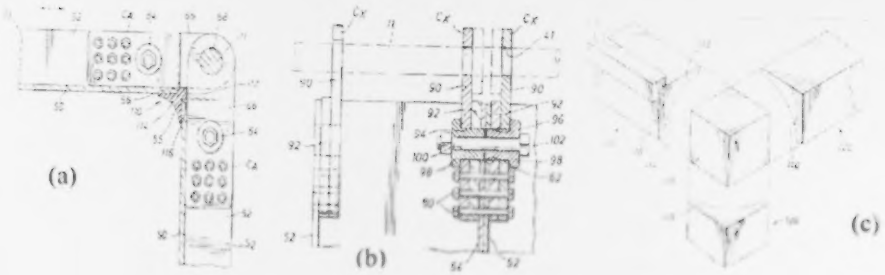

Figure 9. *Types of connections (a and b) and seal (c) [19].*

2.3.2 Modular Hyperbaric Chamber

This chamber (Figure 10) is a modular hyperbaric chamber for treatment of four ambulatory patients or one patient on a stretcher and one ambulatory. It includes one spacer module (18) separating two half cylinder modules (10) placed in vertical orientation with their ends closed by rounded covers (12) and a floor (17). The spacer includes two side sections (20), a top section (ceiling) (30), and a bottom section (floor)(40). The chamber requires that all seams must be effectively sealed against gas leakage to maintain a desired pressure level (at least 3 ATA). According to the inventor [20], all the connections may be lined with a suitable seal, gasket or fluid sealant. One of the capabilities of the concept is the ability to increase its size by adding spacer modules between the half cylinder modules. However, the number of additional spacers depends on the overall structural capability of the chamber.

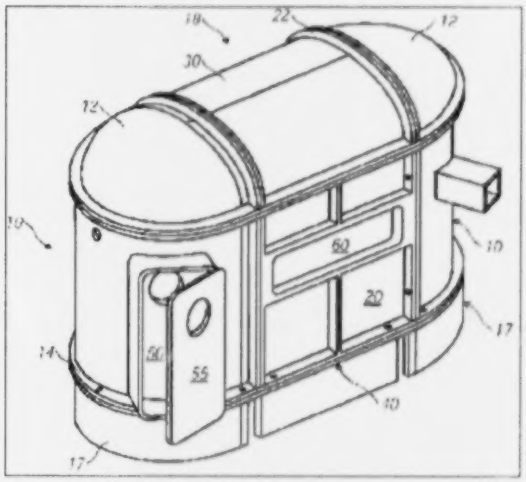

Figure 10. *Modular hyperbaric chamber with entry and supply airlocks and window [20].*

The chamber may include a pressure lock entry with an external door and a full-sized horizontally sliding interior door, allowing the entrance and exit of patients in wheel chairs and on litters. This design can provide space for an inside medical attendant and for approximately 4 ambulatory patients or one litter and one ambulatory patient. Side windows and roof windows can be included to bring in additional light.

Status: *Patent (2002)*
Inventor and Owner: *Jack Robert Maison*

2.3.3 Improved Hyperbaric Chamber

This chamber (Figure 11) is a lightweight, portable, inflatable and collapsible hyperbaric chamber capable of maintaining pressures within the range of about 0.2 up to 22 psi greater than ambient (≤ 2.5 ATA). According to the patent [21], its length is about 80 inches and the circumference is typically about 74 inches. Thus the diameter is about 24 inches. It uses at least two zippers, one of which is a sealing zipper, and a heavy fabric (at least about 20 oz/sq. yd) reinforcing outer layer.

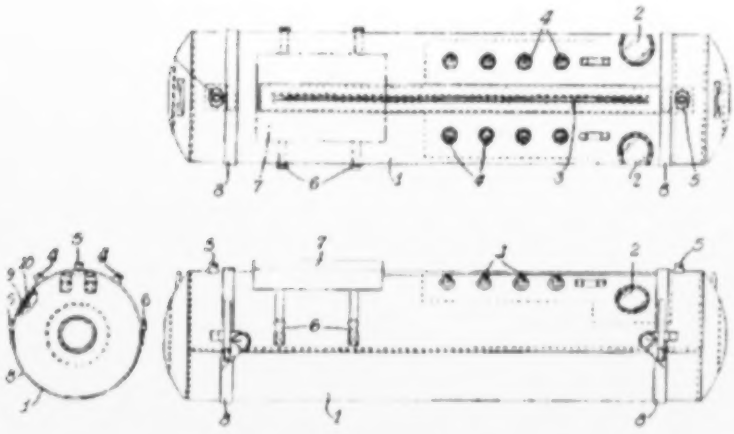

Figure 11. *Improved hyperbaric chamber [21].*

Status: *Patent (1997)*
Inventor: *James W. Bower*
Invention Owner: Portable Hyperbarics Inc.

2.3.4 Hyperbaric Chamber: Exerciser

With a diameter of 2.44 m (8 ft), this spherical hyperbaric chamber is portable and compact (Figure 12). It allows a person to perform endurance exercise at barometric pressures from 0 to 10 psi greater than ambient. Composed of two shells, the material used for the inner shell is air-impermeable and flexible. The outer shell is sturdy to support the pressure stress. The circular base, with a diameter of 1.33 m (4 ft), is made of vinyl.

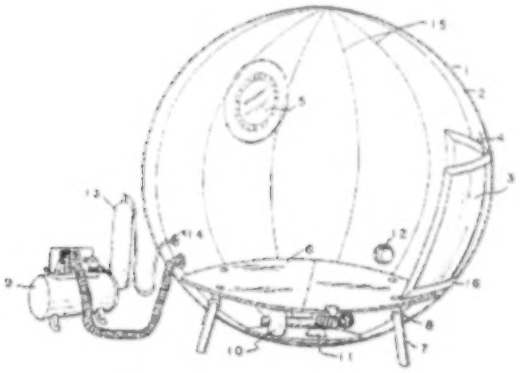

Figure 12. *Hyperbaric chamber: Exerciser [22 and 23].*

Status: *Patent (1994)*
Inventors: *Igor R. Gamow and Geoffrey A. Geer*
Invention Owner: Portable Hyperbarics Inc.

2.3.5 Portable Collapsible Recompression Chamber

This hyperbaric chamber (Figure 13) is portable and collapses into a small space. It provides emergency treatment and safe transportation of divers suffering from DCS. With a circular cross section and cylindrical form, this chamber is capable of receiving one patient on a stretcher. It has three telescoping sections with O-ring seals and telescoping side rails which are used as an expansion bar to pre-seal the chamber and also to serve for lifting.

Status: *Patent (1973)*
Inventor: *Peter Nielsen*
Invention Owner: The US Secretary of the Navy, Washington, D.C. USA

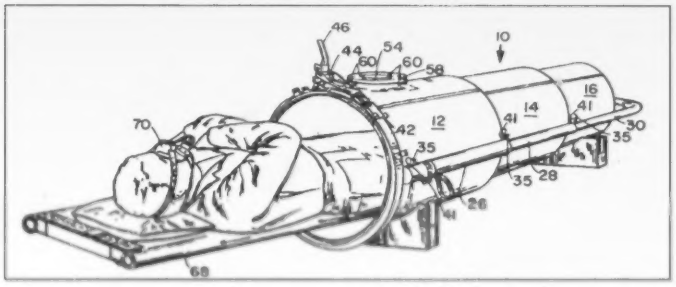

Figure 13. *Collapsible (telescopic) hyperbaric chamber [24].*

2.3.6 Emergency Inflatable Recompression Unit

This portable and inflatable hyperbaric chamber (Figure 14) provides temporary treatment for one diver and transportation to a permanent recompression station. It also provides an elongated entrance for easy access and egress. The chamber is made of a high-strength pressure-proof rubber-coated material.

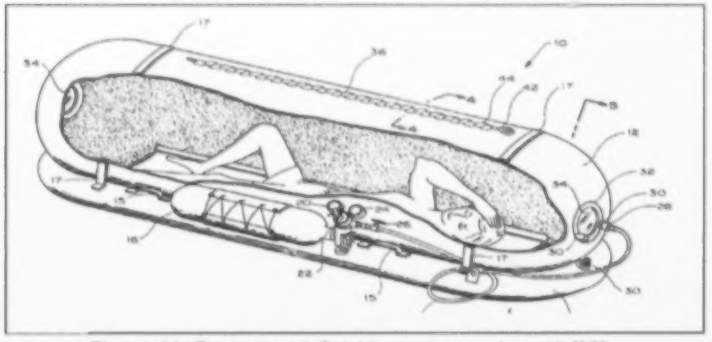

Figure 14. *Emergency Inflatable recompression unit [25].*

Status: *Patent (1973)*
Inventor and owner: *Donald Miller*

2.3.7 Portable Collapsible Recompression Chamber

This portable and inflatable hyperbaric chamber provides temporary treatment for one diver. As shown in Figure 15, it is composed of two principals components: a cylindrically shaped elongated bag (11) and a head panel with a variety of gas transfer fittings (20). The bag is made of a high-strength and lightweight "plastic-like" material (e.g. "Mylar" or Polyethylene). A typical thickness will be about 0.025 to 0.250 mm.

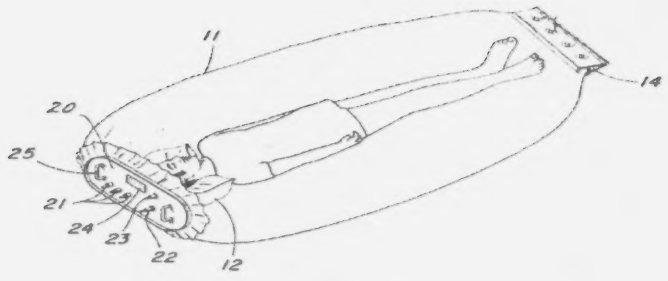

Figure 15. *Portable recompression chamber [26]*

The other end of the chamber is open and large enough to accommodate an unconscious patient. Once the patient is inside the bag, opposite corners at the open end are folded inwardly (Figure 16a), an elongated bar (14) is placed and the bag (11) is rolled over as shown in Figure 16(b). To ensure sealing, a clamp (15) is used over the rolled portion of the bag.

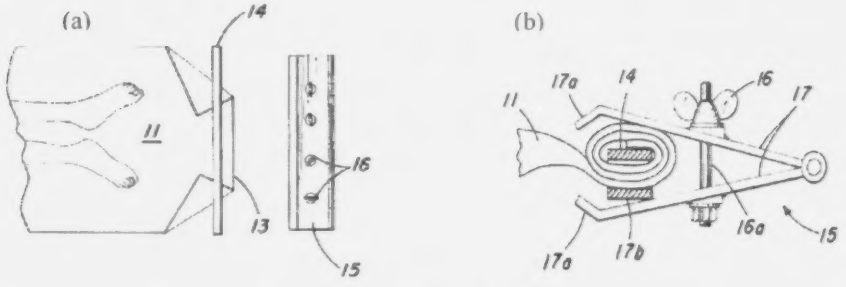

Figure 16. *Open end of the portable recompression chamber [26]; (a): open end and the clamp; (b): clamped opening.*

Status: *Patent (1971)*
Inventor and owner: *Eric V. Bleiken*

2.4 Medical chambers

The medical chambers have been designed to provide low-pressure hyperbaric clinical treatment. Usually they are expected to be safe and easy to use. The typical pressure attained is between 2 and 14.7 psi above ambient (1.1 to 2 ATA).

2.4.1 Gamow bubble

This hyperbaric chamber is referred as a hyperbaric mountain bubble or Gamow's bubble. It is lightweight, portable, inflatable and collapsible. Its shape is cylindrical with hemispherical ends (Figure 17). The Gamow bubble provides relief from altitude sickness pulmonary oedema and rapid decompression.

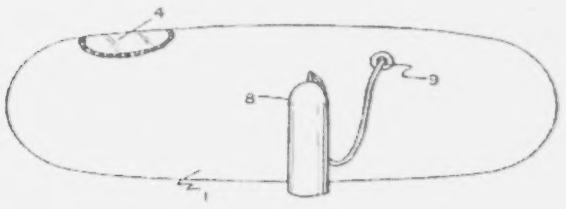

Figure 17. *The Gamow bubble [23].*

Status: *Operational*
Manufacturer: *Hyperbaric Technologies, Inc.*

2.4.2 Emergency Hyperbaric Chamber: Gamow 15

This chamber (Figure 18) provides emergency hyperbaric oxygen (HBO) therapy and transportation under pressure for one subject. It can be used at any location (e.g., diving vessel, helicopter, airplane and ambulance). A SCUBA tank or small oil-free compressor can be used for air pressurization. The chamber is constructed of a heavy-duty polyurethane coated fabric and has an operating pressure of 14.7 psig.

Status: *Operational*
Manufacturer: *Hyperbaric Technologies, Inc.*

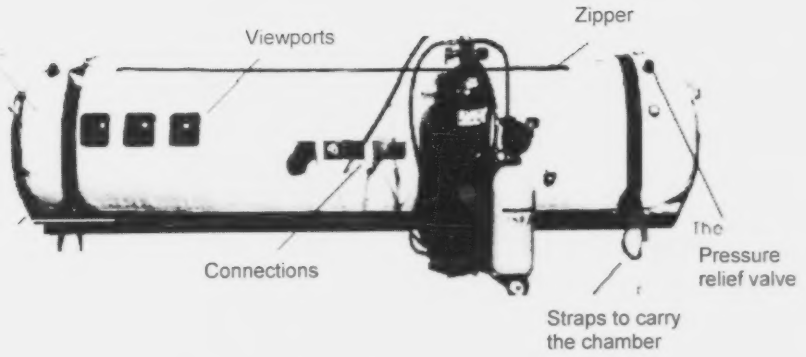

Figure 18. *Gamow 15 [27].*

2.4.3 Chamberlite

The Chamberlite (Figure 19a) provides standard hyperbaric oxygen therapy. According to Shimada et al. [28], this chamber is derived from the Gamow bubble with improved capabilities since the use of new materials made it capable of withstanding higher pressures (7 vs. 2 psi) with a high safety factor and reliability. Indeed, it has been tested up to 4 ATA (or 60 psi), and 16,000 cycles of use. This chamber is collapsible and can fold for transport in its carrying bag (Figure 19 b).

Figure 19. *Chamberlite [29].*

Status: *Operational*
Manufacturer: *Hyperbaric Technologies, Inc.*

2.4.4 Portable Mild Hyperbarics

Oxy Health engineers redesigned the Gamow Mountain Bag to develop an improved portable low-pressure (4 psig or 1.3 ATA) hyperbaric chamber that is intended for the medical community. With better airflow through the chamber and a cylindrical shape, this chamber can provide comfortable treatments and easier entry and egress. Its bladder is fabricated with double-

sided 32 to 44 oz. urethane coated polyester weave fabric for extended operational life. Three chambers with different sizes have been manufactured:

- **Solace 210**: Length: 92 in (2.33 m) and Diameter: 22 in (0.56 m)
- **Respiro 270**: Length: 89 in (2.25 m) and Diameter: 27 in (0.69 m)
- **Vitaeris 320** (Figure 20): The Vitaeris is the largest and can sit two subjects. Length: 93 in (2.36 m) and Diameter: 33.5 in (0.85 m)

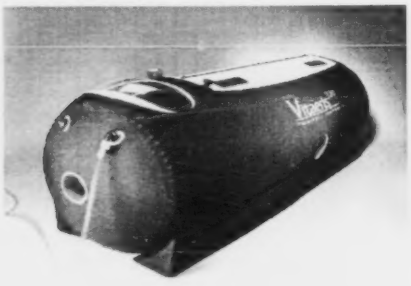

Figure 20. *Portable Mild Hyperbarics: Vitaeris 320 [30].*

Status: *Operational*
Manufacturer: *Oxy Health Corporation*

2.4.5 Tapered Portable Hyperbaric Chamber

As shown in Figure 21, this monoplace chamber is tapered and has four windows for more illumination. Strong nylon and urethane-coated polyester were used to maximize strength and sturdiness, which would allow a pressure of 7 psi above ambient (1.5 ATA).

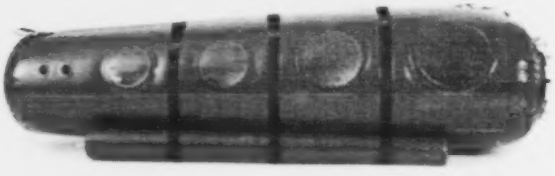

Figure 21. *Portable Hyperbaric Chamber [31].*

Status: *Operational*
Manufacturer: *not known*

3. Discussion

It is well known that 80-100 percent of escapees from a DISSUB will most likely suffer from some form of DCI. The deeper the escape depth is and/or the higher the internal submarine ambient pressure is, the higher is the DCI likelihood [32]. The only effective treatment is immediate recompression in a hyperbaric chamber, preferably on site.

In relation to the above situation, the current deployable hyperbaric capability of the CF is considered highly inadequate. Indeed, Canada possesses enough transportable recompression chambers on each coast to treat only 14 ambulatory survivors of a submarine accident at the scene; the rest (40+) would have to wait and suffer potentially life-threatening consequences from DCI. The number of treated patients could be further reduced when medical attendants are required and/or some of the survivors are not ambulatory. In addition, the few assets that are available are trailer mounted and most importantly, very heavy, therefore lacking flexibility and readiness for short notice deployment.

To improve the transport time and initiate treatment as fast as possible, it is preferable that hyperbaric chambers be portable in an aircraft, preferably a helicopter. In this respect, inflatable or modular ones are the most suitable since they possess advantages over the currently transportable chambers in portability, size, weight and cost. Considering the proven monoplace treatment facilities and the capability of lightweight yet extremely robust flexible composites (such as Kevlar), it is expected that similar technology could be used to design and build large multi-place hyperbaric chambers that can be joined together to treat any number of patients. In addition to its portability and lightness, this chamber would be easily and rapidly assembled to be ready in minimum time.

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Annex A: Summary of the Portable Hyperbaric Chambers

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Table A1. *Manufactured Hyperbaric Chamber Directory*

Total Numb.	Name (Country, Year)	Status*	Pressure	Safety Factor	Shape	Dimension L x D (in.)	Weight	Material	Notes
1.	SOS Hyperlite Hyperbaric Stretcher (UK)	Op	Up to 3.1 ATA 30.5 psig 68.6 fswg	7	Cylindrical	88.5X23.5	88 lbs (Total: 210lbs)	1. **Tube:** Para-aramid fiber (Kevlar®) extremely strong abrasion resistant material (wound in a matrix of silicone rubber). 2. **Domes:** Acrylic/Nylon6	- Inflatable - Monoplace - Operating Temp: -20 to 40 °C - Storage Temp: -60 to 180 °C - Evaluated by Royal Navy, US Navy, US Air Force and NASA
2.	GSE Flexible Hyperbaric (IT)	Op	Up to 6 ATA 73.5 psig 165 fswg	3 approx. (failed at 200 psig when evaluated)	Cylindrical	Length: 84" Diameter: 25", 30", 36", 48" and 60"	114 lbs	- The gasbag is made of a urethane-coated composite polyester cloth. - The outer layer is a web net of cargo straps made of the same polyester material.	- Inflatable - Monoplace - Evaluated by US Navy

(*) Op: Operational

Table A2. *US Government Hyperbaric Chamber Directory*

Total Numb.	Name (Country, Year)	Status	Pressure	Safety Factor	Shape	Dimension L x D (in.)	Weight	Material	Notes
3.	ILC Dover Collapsible Hyperbaric Chamber (USA, 1986)	NASA Prototype	3 ATA 29.4 psig 66 fsw	1.5 to 2 (3)	Cylindrical	76.5X27 (2.1X0.8m)	60.3 lbs	- Bladder: urethane-coated polyester - The restraint: a series of polyester webbings stitched to a polyester fabric substrate.	- Only one was built - Monoplace - Inflatable
4.	Lightweight, Collapsible Hyperbaric Chamber With Airlock (USA, 2001)	NASA Patented + Prototype	2 atm. (Interior)	-	Cylindrical			Multiple layers of lightweight, flexible materials	- Inflatable - Inflatable toroids - One person + One Medical attendant
5.	Modular, Expandable Hyperbaric Chamber System (MEHCS) (USA	Built (US Air Force)	3 ATA		Polygonal	8 ft by 11 ft (? Height by Length)	14000 lbs	Steel	- Modular - Six subjects

Table A3. *Patented Hyperbaric Chamber Directory*

Total Numb.	Name (Country, Year)	Status	Pressure	Safety Factor	Shape	Dimension L x D (in.)	Weight	Material	Notes
6.	Modular Pressure Vessel (USA, 2002)	Patent		-	Polygonal (3 and up sides)	Any size		It can be made of metal, plastic, composites, fibreglass, concrete, etc.	- Modular - May have any size
7.	Modular Pressure Vessel (USA, 2002)	Patent	Expected to withstand at least 3 ATA	-	Two half cylinder modules + spacer module	12ft long and 7 ft wide and 7 ft interior height		Steel (material composites could be used)	- Modular - 4 ambulatory patients - May have any size
8.	Improved Hyperbaric Chamber (USA, 1997)	Patent	Up to 22 psig	-		80"X23.5"	20 to 30 oz./sq. yd	Polymeric materials: polyamides (nylon 6, 66,610, 612) and polyesters (polyethylene terephthalate and polybutylene terephthalate) Impermeability: coated with a polymeric material (polyurethane or vinyl)	- Inflatable - With 2 zippers
9.	Hyperbaric Chamber (USA, 1990)	Patent	0.2 to 10 psig	-	Spherical			- Outer shell: air impermeable nylon fabric - Inner shell air impermeable vinyl	- Inflatable
10.	Portable Collapsible Recompression Chamber (USA, 1973)	Patent		-	Cylindrical				Three Telescoping sections
11.	Emergency Inflatable Recompression Unit (USA, 1973)	Patent		-	Cylindrical	90"X28"		High-strength pressure – proof rubber-coated fabric	- Inflatable - Sealing Zipper

Table A4. *Medical Hyperbaric Chamber Directory*

Total Numb.	Name (Country, Year)	Status*	Pressure	Safety Factor	Shape	Dimension L x D (in.)	Weight (lbs)	Material	Notes
12.	Gamow Bag	Op	1-2 psig	-	Cylindrical with Hemispherical ends			- Outer shell: air impermeable nylon fabric - Inner shell air impermeable vinyl	- Fully portable - Altitude sickness treatment for one person
13.	Gamow 15	Op	2 ATA 14.7 psig	-	Cylindrical	84 x 21	5	Heavy duty polyurethane coated fabric	
14.	Chamberlite (USA)	Op	1.5 ATA 7 psig	Up to 4 ATA 60 psi	Cylindrical	84 x 21	45	Polyurethane fabric	- Fully portable - Monoplace - 4 windows
15.	Portable Mild Hyperbaric Chamber (USA) : Respiro 210	Op	1.3 ATA 4 psig	-	Cylindrical with Hemispherical ends	89 x 27	29.5	28-30oz urethane reinforced material.	- Self treatment - Monoplace - 4 windows
16.	Portable Mild Hyperbaric Chamber: Solace 270 (USA)	Op	1.3 ATA 4 psig	-	Cylindrical with Hemispherical ends	99 x 22	27	Double sided highly durable 32-35oz double reinforced urethane material	- Self treatment - Monoplace - 4 windows
17.	Portable Mild Hyperbaric Chamber: Vitaeris 320 (USA)	Op	1.3 ATA 4 psig	-	Cylindrical with Hemispherical ends	93 x 33.5	38	Double sided highly durable 40-44oz double reinforced urethane material	- Self treatment - Two persons
18.	Portable Hyperbaric Chamber	Op	1.5 ATA 7 psig		Cylindrical and Tapered		18	Nylon and urethane coated polyester	- 4 windows - Flatten design

(*) Op: Operational

Annex B: Detailed Chambers Specifications

Table B1. *Hyperbaric Chamber specifications*

Chamber's name::	**SOS Hyperlite**	**GSE**	**ILC Dover**	**Chamberlite**
Design Code	ASME PVHO-1/Code Case 6	NA	NA	NA
Working Pressure: (bar / psig / fsw)	1.8 / 26.7 / 60	5.1 / 73.5 / 165	2.03 / 29.5/ 66	0.5 / 7 / 16
Length x Diameter:	2248 x 597 mm 88.5 x 23.5 in	2134 x (635 to 1524) mm 84 x (25 to 60) in	2100 x 800 mm 76.5 x 27 in	2134 x 533 mm 84 x 21 in
Tube thickness:	3.8 mm (0.15 in)	Unknown	Unknown	Unknown
Dome thickness:	22.9 mm (0.9 in)	Unknown	Unknown	No
Weight: (Vessel only)	40 kg (88 lbs)	51.6 kg	27.3 kg (approx.)	20.5 kg
Materials: - **Tube** - **End Domes**	- Para-aramid (Kevlar®) /Silicone - Acrylic/Nylon 6	- Urethane-coated composite polyester with webbing - Aluminium	- Urethane-coated polyester with polyester webbing stitched to a polyester fabric - NA	- Polyurethane fabric - No end domes
Pressurization Gas:	Compressed air	Compressed air	Unknown	Compressed air
Treatment Gas:	Oxygen	Oxygen	Unknown	Oxygen
BIBS:	Yes	Yes	Unknown	Yes
Communication:	Two-way	Two-way	Unknown	Two-way
View ports:	Yes (end only)	Yes (end only)	Yes (end only)	Yes
NATO flange:	No	Yes	No	No
Medical Lock:	Yes	Yes (Optional)	No	No
Can be linked:	Yes	Yes	No	No
Packed Volume:	**Two Cases:** - 670 x 670 x 570 mm and 57 kg - 640 x 640 x 290 mm and 38 kg	Diameter x Length: 736.6 x 406.4 mm 29 x 16 in	Height x Length x Depth: 660.4 x 660.4 x 86.4 mm 26 x 26 x 3.4 in	Height x Length x Depth: 711 x 762 x 305 mm 12 x 28 x 30 in

Annex C: Directory

GSE Flexible Hyperbaric

Company: GSE Giunio Santi Engineering S.R.L. (IT)
Address: Piazza Bergamo #18, Zingonia, Italy
Telephone: +39-035-885605
Facsimile: +39-035-882629
E-Mail: guisanti@tin.it

Hyperbaric Chamber: the Exerciser (patent)

Inventors: Igor R. Gamow and Geoffrey A. Geer
Invention Owner: Portable Hyperbarics Inc.
Address: PO Box 510, Ilion, NY 13357, USA

Hyperbaric Chamber: the Gamow's bubble and the Gamow 15

Inventors: Igor R. Gamow and Geoffrey A. Geer
Invention Owner: Portable Hyperbarics Inc.
Manufacturer: Hyperbaric Technologies, Inc.
Address: One Sam Stratton Road, P.O. Box 69 – Amsterdam, New York 12010
Telephone: (518) 842-3030
Fax: (518) 842-1031
Email: plewis@bretonindustries.com

Improved hyperbaric chamber (patent)

Inventor: James W. Bower
Invention Owner: Portable Hyperbarics Inc.
Address: PO Box 510, Ilion, NY 13357, USA

ILC Dover Collapsible Hyperbaric Chamber

Company: ILC Dover, Inc.
Address: One Moonwalker Road – Frederica, DE 19946-2080, USA
Telephone: +1(302) 335-3911
Facsimile: +1 (302) 335-1320
Customer Service: 1-800-631-9567
Contact email: grahaw@ilcdover.com
Webpage: http://www.ilcdover.com

Lightweight, Collapsible Hyperbaric Chamber With Airlock (patent)

Inventor: William C. Schneider, James P. Locke, and Horacio M. De La Fuente

Invention's Owner: The Administrator of the National Aeronautics and Space Administration (NASA)
Address: Lyndon B. Johnson Space Center, Houston, Texas, USA

Modular, Expandable Hyperbaric Chamber System (MEHCS)

Inventor: The US Air Force, USA
Invention Owner: The US Air Force USA

Modular and Polygonal Pressure Vessel (patent)

Inventor and owner: Audley L. Aaron
Correspondence Address: Browning Bushman P.C.
5718 Westheimer, Suite 1800, Houston, TX 77057
USA

Modular Hyperbaric Chamber (patent)

Inventor and owner: Jack Robert Maison
Address: 3307 Hunters Sound, San Antonio, TX 78230 USA

Portable Mild Hyperbaric Chamber

Company: Oxy Health Corporation
Address: 12007 Los Nietos Road, #9 Santa Fe Springs, CA 90670 USA
Telephone: +1 877.789.0123
Facsimile: +1 562.906.8885
E-Mail: info@oxyhealth.com
Webpage : http://www.hyperoxy.com/

SOS Hyperlite Hyperbaric Stretcher

Company: SOS Limited
Address: 612 Watford Way, London, NW7 3JH, England
Telephone: +44 (0) 20 8959 8959
Facsimile: +44 (0) 20 8959 7971
E-Mail: SOS@hyperlite.co.uk
Webpage : http ://www.hyperlite.co.uk

Tapered Hyperbaric Chamber

Telephone: (808) 573-8166
Email: info@hyperbaric-oxygen-chamber.com
Webpage: www.hyperbaric-oxygen-chamber.com/

List of symbols/abbreviations/acronyms/initialisms

AFRL	US Air Force Research Laboratory (USA)
AGE	Arterial Gas Embolism
ASME	American Society of Mechanical Engineering
ATA	Atmospheres Absolute pressure
atm	Atmospheres
bar	= 1/1.013 atm
BIBS	Built-in breathing system
CF	Canadian Forces
cm	Centimetre
DCI	Decompression Illness
DCS	Decompression Sickness
DERA	Defence Evaluation and Research Agency (UK)
DISSUB	Distressed Submarine
DSRV	Deep Sea Rescue Vehicle
ft	Feet
fsw	Feet of seawater
GSE	Giunio Santi Engineering
IT	Italy
in	Inch
kg	Kilogram
MEHCS	Modular and Expandable Hyperbaric Chamber System

m	Meter
mm	Millimetre
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NEDU	Navy Experimental Diving Unit (USA)
Op	Operational
oz	Ounce
PVHO	Pressure Vessel for Human Occupancy
psi	Pound per square inch
psig	Pound per square inch gauge
SCUBA	Self-Contained Underwater Breathing Apparatus
TUP	Transfer Under Pressure
UK	United Kingdom
USA	United States of America

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14. ABSTRACT

(U) To protect divers and submariners suffering from decompression illness (DCI) in remote areas, far from a medical centre, it is critical to begin hyperbaric therapy as soon as possible. Since many fatalities involved in diving accidents result from delays in treatment, portable lightweight hyperbaric chambers have been developed. With modern technology, such as new materials, and with different operational conditions and dimensions, recompression chambers can be designed to operate in any location, such as on a ship, in a helicopter, or on an airplane, as a hyperbaric stretcher to evacuate the patient under pressure. There are a number of such chambers. The objective of the present report is to review and describe the principal characteristics and capabilities of all existing portable hyperbaric chambers, including the ones used for medical and private operations. The literature review has identified approximately 20 collapsible chambers which are either inflatable or modular. Some of them are fully operational while others are still in prototype or patent state. The outcome of this review is to identify methods and new developments in engineering with the aim of designing and building a new multi-person hyperbaric emergency treatment facility for submarine escape and rescue.

(U) Pour protéger les plongeurs et les sous-mariniers souffrant de la maladie de décompression en régions éloignées, loin d'un centre médical, il est critique d'amorcer un traitement hyperbare le plus tôt possible. Comme de nombreux décès ou lésions permanentes associés à des accidents de plongée sont dus à des retards dans la mise en route d'un traitement, des caissons hyperbares légers portatifs ont été mis au point. Grâce à la technologie moderne, notamment à de nouveaux matériaux, et en tenant compte de différentes dimensions et conditions opérationnelles, il est possible de concevoir des caissons de recompression qui peuvent fonctionner partout, p. ex. sur un navire, un hélicoptère, un aéronef, ou servir de brancard hyperbare pour évacuer le patient sous pression. Il existe un certain nombre de caissons de ce type. L'objectif du présent rapport est de passer en revue et de décrire les principales caractéristiques et fonctions de tous les caissons hyperbares portatifs existants, y compris ceux utilisés pour des opérations médicales et privées. Un dépouillement de la littérature nous a permis de recenser environ 20 caissons gonflables ou modulaires. Certains d'entre eux sont tout à fait opérationnels alors que d'autres en sont encore au stade du prototype ou du brevet. Le but de cette revue de la littérature est de déterminer les méthodes et les innovations en génie qui permettraient de mettre au point et de construire de nouvelles installations de traitement hyperbare d'urgence pour plusieurs personnes qui pourraient servir lors d'évacuation et sauvetage de sous-marins.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) Hyperbaric Chamber; Hyperbaric Treatment Facility, Recompression Chamber; Decompression Illness, DCI